Interlayer exchange coupling

1. Discoveries

The exchange coupling of magnetic films across metallic interlayers was first observed in 1986 for Dy and Gd films separated by Y interlayers and for Fe films separated by Cr interlayers. For ferromagnetic films like those of Gd and Fe, the coupling leads to parallel or antiparallel alignment of the magnetizations on opposite sides of the interlayer, depending on the interlayer thickness D, as seen in Fig. 1(a) and (b) re-

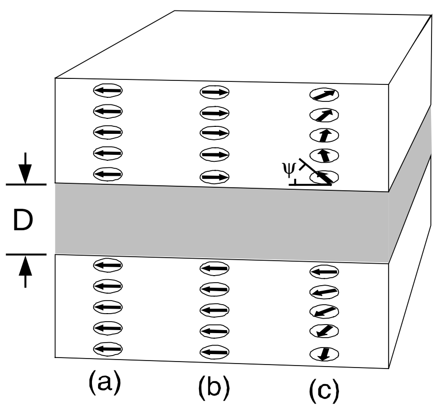

Fig.1 Coupling between magnetic films across metallic interlayer (dark shaded). Encircled arrows indicate moments in monolayer sheets parallel to the interfaces. The arrows indicate ferromagnetic coupling across the interlayer in (a) and antiferromagnetic coupling in (b). The magnetic coupling of films with a helical magnetic structure shown in (c) leads to a phase angle ψ

spectively. For obvious reasons, the coupling leading to (a) is called "ferromagnetic"(F) and to (b) "antiferromagnetic" (AF). For films with helical magnetic structure like Dy, the coupling leads to an angle ψ between the magnetic moments on both sides of the Y interlayer, which depends on the Y thickness, as seen in Fig.1 (c). The actual alignment is also affected by other interactions like anisotropy or external field H_{ext}. Large enough fields H_{ext} overcome the coupling and align the magnetizations parallel.

In 1990, it was established that the oscillation of the magnetic coupling between F and AF alignment, as a function of interlayer thickness, is a general phenomenon of transition metal ferromagnets separated by non-magnetic interlayers. Previously oscillations had only been seen for Gd separated by Y. The discovery in 1988 of the Giant Magnetoresistance (GMR) effect in the Fe/Cr system (see contribution by A. Fert in this volume) led to enhanced interest in the magnetic coupling of transition metal ferromagnets because of the many applications of GMR.

2.Theoretical Models

Interlayer exchange coupling is believed to be an indirect exchange interaction mediated by the conduction electrons of the spacer layer. It is closely related to the Ruderman-Kittel-Kasuya-Yoshida (RKKY) interaction, between localized moments mediated by the conduction electrons of a host metal. The essential ingredients of the RKKY interaction, a localized spin-polarized perturbation and a sharp Fermi surface, lead to the well-known coupling oscillations. Like the exchange coupling in the rare earth metals themselves, the magnetic coupling of Gd, Dy, Ho, and Er through Y and Lu spacer layers has been described by the RKKY interaction.

For transition metal ferromagnets separated by paramagnetic interlayers, the description of the coupling needs to be modified. A phenomenological description of the coupling proposed to explain the experimental observations gives the interlayer coupling energy, E_i, per unit area as

$$E_i = -J_1 \cos(\vartheta) - J_2 \cos^2(\vartheta) \qquad (1)$$

Here ϑ is the angle between the magnetizations $\vec{M}_1$ and $\vec{M}_2$ of the films on both sides of the spacer layer.

The parameters J_1 and J_2 describe the type and the strength of the coupling. If the term with J_1 dominates, then from the minima of Eq.1 the coupling is F (AF) for positive (negative) J_1. If the term with J_2 dominates and is negative we obtain 90°-coupling. The first term of Eq.(1) is often called the bilinear coupling and the second the biquadratic coupling.

The microscopic mechanism leading to the bilinear exchange coupling J_1 has essentially the same physical origin as the RKKY interaction. However, one must consider the itinerant nature of electrons in transition metal ferromagnets which gives rise to the spin-split band structure and spin-dependent reflectivities at the paramagnet/ferromagnet interfaces. The spin-dependent reflectivity is illustrated in Fig.2 (a), where it is assumed that electrons with their spins parallel (antiparallel) to the magnetizations $\vec{M}_1$ and $\vec{M}_2$ are weakly (strongly) reflected at these interfaces. This spin-dependent reflection at the interfaces gives rise to spin-dependent quantum well states that cause an oscillatory polarization in the interlayer. As a result there are spin-dependent interference effects like the formation of standing electron waves for certain interlayer thicknesses as indicated in Fig.2 (a). Due to the similarity of the arrangement in Fig.2 (a) with an optical Fabry Perot interferometer this is sometimes also called the Fabry Perot model of oscillatory coupling. Oscillations in the coupling observed as the thickness of a magnetic layer or other overlayer is varied are explained by additional spin-dependent interference effects.

The predominant contribution to the coupling is from electrons with wavevectors, Q_i, that are critical spanning vectors of the Fermi surface of the interlayer material, i.e., vectors in the direction perpendicular to the interface that connect two sheets of the Fermi surface parallel to each other. For the Fermi surface of Au shown in Fig 2b, there are two such vectors in the [100] and one vector in the [111] direction. The periods of the oscillatory coupling are given by $\Lambda = 2\pi / Q_i$ and thus are determined solely by the electronic properties of the interlayer material.

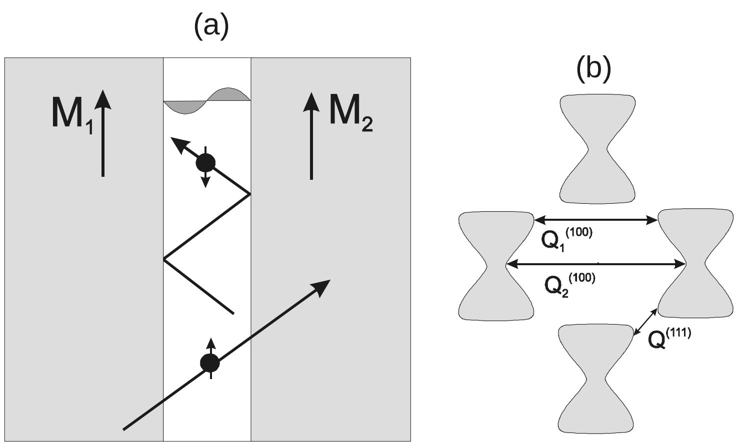

Fig.2 Illustration of spin-dependent reflectivity at the nonmagnetic/magnetic interfaces for the explanation of oscillatory coupling in part (a). Part (b) shows a cross section of the Au Fermi surface with critical spanning vectors in the [100] and [111] directions.

This quantum well model leads to the following dependence of J_1^i of Eq.1, connected with the i^{th} Fermi surface spanning vector Q_i, on the interlayer thickness D:

$$J_1^i = J_0^i \sin(Q_i D + \phi_i)/D^2 \qquad (2)$$

The amplitude J_0^i includes Fermi surface geometry factors and interface reflection probabilities. Good parallelism of the parts of the Fermi surface at the endpoints of a critical spanning vector will contribute to large amplitudes of the corresponding oscillatory coupling. This so-called "nesting" effect results in a decrease of the coupling with interlayer thickness as D^{-1} rather than the more typical D^{-2}. If, due to favorable band matching, electrons with one spin have good transmission at the interfaces and the other spin good reflection, then the result will be large amplitudes in oscillatory coupling strength. This is thought to be the case for the coupling of Co across Rh and Ru interlayers (see table 1). In principle, the quantum well model can be extended to non-metallic spacers using a complex Fermi surface, but materials difficulties have limited experimental work in this area.

The theoretical description of magnetic coupling assumes perfect interfaces. Experimentally, there is always some disorder at the interfaces. The interaction of Eq. 2 is defined at each discrete interlayer thickness $D = nd$ where d is the spacing of neighboring atomic layers in the interlayer. The direction of magnetization in a magnetic layer can only change over a finite lateral distance l comparable to a domain wall width. If there are interlayer thickness fluctuations on a lateral length scale smaller than this magnetic response length l, the observed coupling strength is an average over regions of different thickness,

$$\bar{J}_1(t) = \sum_i \sum_n P(t,n) J_i(n) \qquad (3)$$

where $P(t,n)$ is the fraction of the interlayer area that is n layers thick when the average thickness is *t*. Short period oscillations of the coupling are averaged out more readily than long period oscillations and therefore are only observed in samples with relatively smooth interfaces. Thickness fluctuations, and also interfacial disorder on a finer scale due to alloying, lead to a measured magnetic coupling that is weaker than that expected theoretically.

Although J_2 of the biquadratic coupling term in Eq. 1 can be of intrinsic origin, most experimental results to date are well explained by a model in which the biquadratic coupling is an extrinsic effect due to the thickness fluctuations of the interlayer. For example, if the bilinear coupling varies spatially due to the thickness fluctuations, the sum of the intralayer coupling energy (exchange stiffness) and interlayer coupling energies is minimized when the magnetizations of the layers fluctuates about their average directions. The energy is lowered the most when the average magnetizations of the two layers are perpendicular. This biquadratic coupling leads to observation of 90° coupling when the average bilinear coupling is small.

The RKKY description of magnetic coupling in rare earth multilayers and the quantum well model of coupling in transition metal multilayers assume that the electrons in the spacer layers are non-interacting. On the other extreme, the electrons of the interlayer may be strongly interacting, as for example local moments coupled to each other in antiferromagnetic Mn. A phenomenological model for this situation, known as the torsion or proximity model, has been proposed that treats the magnetic nature of the spacer layer and predicts slightly different observable behavior.

The appropriate description of the coupling may fall between the assumed non-interacting electrons of the interlayer in the RKKY and the quantum well models and the strongly coupled local moments of the torsion model. A model including an induced spin density wave was proposed to explain experiments on the coupling of Dy through Y and Lu. There is also strong evidence from the temperature dependence of the coupling in an Fe whisker-based Fe/Cr/Fe trilayer that the Cr electrons are in an interacting intinerant spin density wave state.

3. Experimental Methods, Examples

Polarized neutron diffraction provided the initial evidence for the oscillatory exchange coupling of superlattices of Gd layers separated by Y interlayers. These measurements were supplemented by magnetization measurements that show the remanent magnetization and the saturation magnetization oscillating as a function of Y thickness.

Coupling of rare earths with complex spin structures like Dy, Ho, and Er, through interlayers of Y and Lu can be studied with unpolarized neutron diffraction because there are distinct magnetic scattering peaks deriving from the incommensurate magnetic order. The phase and chirality of the helical spin structure of Dy is preserved through Y spacer layers over 10 nm thick in superlattices grown along the c-axis direction. The stronger coupling found for c-axis superlattices compared to a- or b-axis structures was attributed to the directional properties of the interlayer Fermi surface.

Superlattices as well as simpler trilayer structures have been used to investigate coupling of transition metal ferromagnets. As an alternative to preparing many superlattices or trilayer samples each with a specific interlayer thickness, it is possible with a trilayer to grow the spacer layer in the form of a wedge with continuously varying thickness. An example of such a structure is shown in Fig. 3 (a).

The periods of the oscillatory interlayer coupling can be determined from the variation of the magnetic domains with changing thickness of the interlayer wedge. The domains can be detected optically with the magneto-optic Kerr effect or by means of spin-polarized electrons using scanning electron microscopy with polarization analysis (SEMPA).

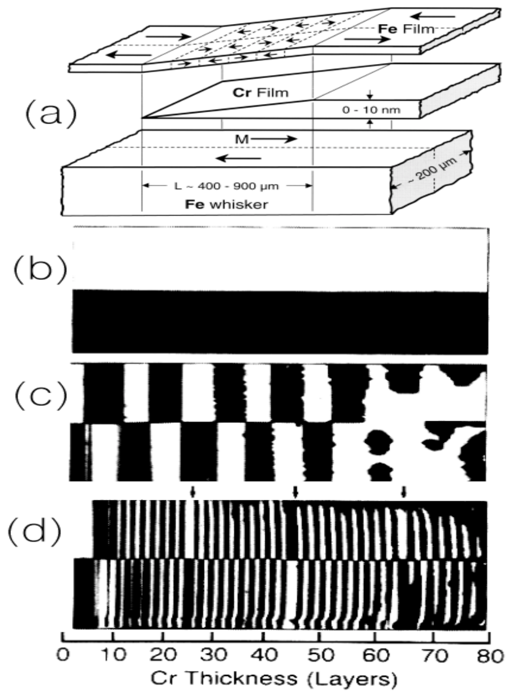

Fig.3 Magnetic domains in Fe/Cr/Fe samples seen by means of SEMPA, which display oscillatory coupling. Sketch of the sample seen in part (a). Domains are observed in the bare whisker substrate (b) and in the upper Fe film grown at 30°(c) and at 350°(d).

Figure 3 (b-d) displays SEMPA magnetization images in which the black (white) regions correspond to magnetizaton to the left (right). Note that in part (b) the bare Fe whisker displays two domains with a 180° wall in between. Parts (c) and (d) show domains in the upper Fe film, separated from the whisker by a Cr spacer grown at an Fe whisker substrate temperature of 30°C and 350°C, respectively. At 350°C, the Cr grows in a layer-by-layer mode forming a very smooth interface while the low temperature growth leads to a rougher Cr growth.

The striking difference in the magnetic domain patterns of parts (c) and (d) indicates how thickness fluctuations affect which periods of the magnetic coupling can be observed. For the near ideal growth in (d), both a short and long period coupling can be observed with the short period clearly dominating. In (c) the short period coupling is averaged out by thickness fluctuations as described by Eq. 3, and only the long period is observed. The long and short periods were determined to be 12 ML and 2.1 ML respectively. The short period oscillations derive from a wavevector connecting strongly nested regions of the Cr Fermi surface. The slight difference between this Fermi surface critical spanning wavevector and the lattice wavevector leads to phase slips in the short period oscillations at the Cr thicknesses indicated by arrows.

For a measurement of coupling strengths, it is necessary to apply a magnetic field. The simplest and most frequently employed method is a measurement of the remagnetization curve where the strength of the coupling is determined from the field required to switch from AF to F coupling. A measurement essentially of this type can be made in parallel with a sample struc-

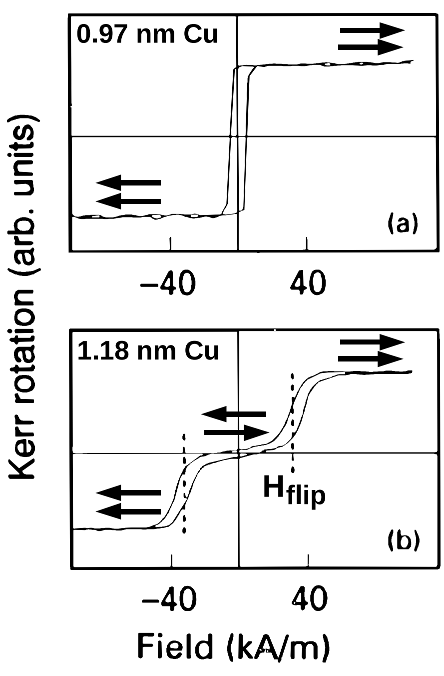

Fig.4 Remagnetization curves of a Co/Cu/Co trilayer structure with ferromagnetic coupling in part(a) and antiferromagnetic coupling in part(b).

ture as in Fig. 3(a) by using magneto-optical microscopy; the coupling strength is determined from the external field required to switch the antiferromagnetically coupled domains causing them to disappear. Alternatively, one can measure the magnetic coupling by determining the frequency shifts of coupled spin wave modes, which represent the restoring forces caused by the coupling.

Remagnetization curves from trilayers consisting of two 6 nm fcc Co films separated by two different thicknesses of Cu are displayed in Fig. 4. The coupling is ferromagnetic in Fig. 4(a) and the films always reverse their magnetizations in unison. In Fig. 4(b), the strength of the antiferromagnetic coupling is determined by the field H_{flip} where the coupling changes

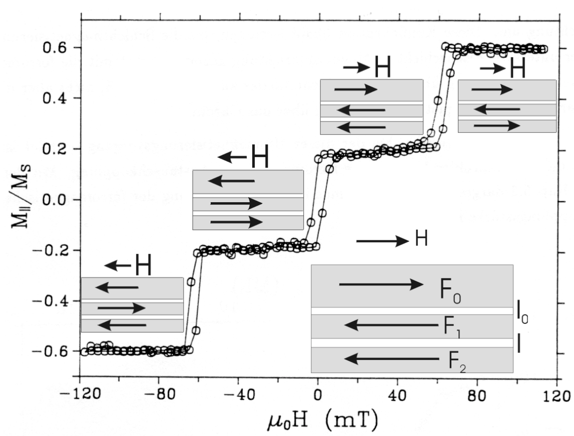

Fig.5 Structure (lower right side) and typical remagnetization curve of a Fe/Au/Fe sample with spin engineering

from AF to F. In order to measure the strength of the coupling in ferromagnetically coupled regions by remagnetizaton curves, it is necessary to resort to a technique known as "spin engineering". To measure the coupling between two ferromagnetic films F_1 and F_2 across an interlayer I, an additional thick ferromagnetic film F_0 is added such that it is strongly antiferromagnetically coupled to F_1 by using a proper interlayer I_0, as shown in Fig 5. F_1 and F_2 can be held with their magnetizations opposite to the external field H until H overcomes the ferromagnetic coupling and reverses

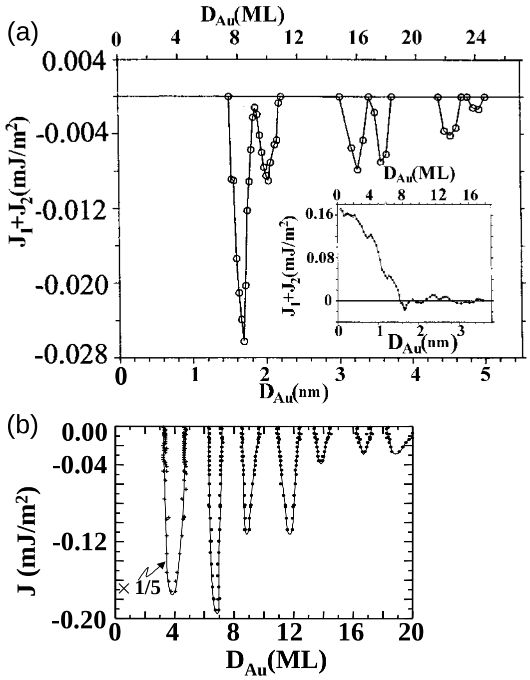

Fig. 6 Coupling strength as a function of thickness in Fe/Au(wedge)/Fe on (a) Ag-buffered GaAs substrate and (b) on Fe whisker. The inset in (a) includes ranges where the coupling is ferromagnetic.

the magnetization of F_2 thereby determining the ferromagnetic coupling across I.

In Fig.6 (a) we see the result of an evaluation of remagnetization curves for a Fe/Au_{wedge}/Fe structure grown on a Ag-buffered GaAs(100) substrate. The spin engineering technique has been used to determine the positive values of the coupling. The coupling is strongly ferromagnetic in Fig.6 (a) for small d_{Au}, probably due to pinholes and magnetic bridges. For increasing d_{Au} ferromagnetic coupling quickly decreases, until there are oscillations around zero. Two periods of oscillation are superimposed with an amplitude that is attenuated as a function of the interlayer thickness.

Measurements of the coupling strength in a Fe/Au_{wedge}/Fe trilayer grown on a Fe whisker, by observing the disappearance of antiferromagnetically coupled domains in a Kerr microscope, are shown in Fig. 6 (b). Two periods of oscillatory coupling, 2.48 ML and 8.6 ML, were determined from the data. Both the samples used in Fig. 6 (a) and (b) were grown very carefully; the stronger coupling for the Fe whisker sample is indicative of the better growth occurring naturally on that substrate. The data of Fig. 6 (b) were further analyzed taking into account thickness fluctuations to obtain “unaveraged” values to compare with theory; the coupling strength for the short and long period oscillations was found to be 60% and 15% of that calculated respectively.

In table 1 we have compiled some measured values for interlayer coupling strengths and periods. As shown in Fig. 3, the thickness fluctuations can obscure the short period oscillations by averaging but do not

Table 1.
Observed coupling strengths and periods

sample	***maximum strength in mJ/m^2 at (thickness) in nm***	***periods in ML and (nm)***
Co/Cu/Co(100)	0.4 (1.2)	2.6(0.47),8(1.45)
Co/Cu/Co(110)	0.7 (0.85)	9.8(1.25)
Co/Cu/Co(111)	1.1 (0.85)	5.5(1.15)
Fe/Au/Fe (100)	0.85 (0.82)	2.5(.51),8.6(1.75)
Fe/Cr/Fe (100)	>1.5 (1.3)	2.1(0.3),12(1.73)
Fe/Mn/Fe (100)	0.14 (1.32)	2(0.33)
Co/Ru(0001)	6 (0.6)	5.1(1.1)
Co/Rh/Co (111)	34 (0.48)	2.7(0.6)
Co/Os(111-text)	0.55 (0.9)	7(1.5)
Co/Ir(111)	2.05 (0.5)	4.5(1.0)

change the periods which are determined by the interlayer Fermi surface. On the other hand, the thickness fluctuations dramatically affect the coupling strength, as seen from Fig 6, and thus the values listed in Table 1 are representative coupling strengths for specific samples. Table 1 gives the maximum observed coupling strength, $\left|J_1 + J_2\right|$, and the spacer layer thickness in nm at which it was measured. The coupling strength also decreases with increasing temperature.

4. Applications

Applications of interlayer exchange coupling have been suggested. For example, antiferromagnetic coupling can be used in "artificial" antiferromagnets, i.e., layered structures of ferromagnetic films, coupled strongly antiferromagnetically, such that the total moment disappears. The advantage of such a structure as compared to a natural antiferromagnet is the fact that it is easier to prepare an uncompensated surface with a net magnetic moment. This is of interest in the context of "exchange anisotropy" used for pinning the magnetization

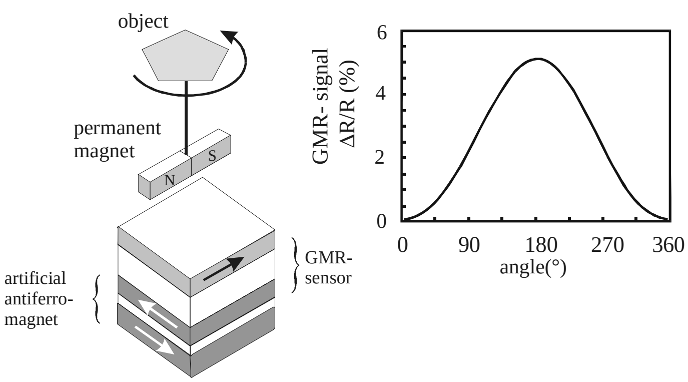

Fig.7 Sensor for the measurement of the rotational angle of an object by means of the GMR effect which makes use of an artificial antiferromagnet on the basis of antiferromagnetic coupling

unidirectionally. At the surface of a natural antiferromagnet the moment can be largely compensated, due to surface roughness or other irregularities. Artificial antiferromagnets can replace natural ones for example in field sensors where they are used to shift remagnetization curves using the exchange anisotropy effect. The application is displayed in the case of a rotational GMR type sensor in Fig.7

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